Acta Futura 10 (2016) 23-35

DOI: 10.5281/zenodo.202160

Acta Futura

Architectural Design Principles for Extra-Terrestrial Habitats

Scott J. Porter* [1], Fiona Bradley[2]

[1] Department of Architecture, University of Strathclyde, Glasgow (Scotland)
[2] School of Engineering, University of Glasgow (Scotland)

Abstract. Future space missions are expected to increase both in their duration and crew population, therefore further advancement in the design understanding of internal and external systems of space habitats is critical. To combat the detrimental effects of long-duration space flights and habitation within enclosed, isolated and confined environments, it is vital that space accommodation is designed to provide a high quality environment which supports the crew both physiologically and psychologically. This research project therefore studies the architectural principles which relate to habitability and their associated design parameters in relation to a proposed concept habitat design on the Moon and Mars. It proposes that there is a requirement for spatial planning guidance and regulations which will assist multi-disciplinary design teams in developing high quality living and working environments for astronauts [11]. It is also postulated that in order to assist with the application of these widely varying parameters into the initial conceptual design process, there would be a great benefit in the publication of an architectural design manual for extra-terrestrial habitats.

1 Introduction

Mars exploration has gained a surge in popularity in the media in recent years due to recent robotic missions such as NASA's Curiosity Rover and concepts such as the Mars One project. The objective of sending humans to the surface of Mars and returning them safely to Earth will however be much more complex than any previous mission undertaken. Indeed the duration alone will significantly exceed that of any previous record of humans in space. To date, the longest period spent in space was undertaken by Russian cosmonaut Valeri Polyakov for a total of just over 437 days. He spent this time aboard the MIR space station from 1994 to 1995 and upon his return he was monitored to study the effects of prolonged exposure to a weightless environment. Due to his rigorous daily exercise regime in space it was found that there was less bone and muscle degradation than had been previously expected [14]. Due to the knowledge gained over many years from the study of astronauts, such as Polyakov, returning from space, it is known that there are a number of uncertainties and significant implications relating to the health of future astronauts selected for missions to Mars. Therefore the design of any accommodation needs to achieve very high levels of habitability and quality in order to minimise any detrimental psychological and physiological stresses. Architectural excellence can be achieved by adopting key architectural

*Corr. authors. E-mails: scott.porter.2013@uni.strath.ac.uk, fiona.bradley@glasgow.ac.uk

design principles such as space, light and comfort as well as addressing technical issues such as structural, mechanical and electronic engineering integrity. Architectural design issues can additionally be sub-divided into specific design parameters such as spatial design, spatial arrangement, lighting design, indirect external viewing methods, interior decor and furnishings. These important criteria have been incorporated into architectural design since antiquity and are still extremely relevant today, being almost universally applied and in many cases strictly employed.

A consequence of the severe limitation on a crew's ability to externally explore the landscape on the extra-terrestrial surface habitat of the Moon and Mars will be the confinement of the astronauts to an indoor environment for the vast majority of their mission. This confinement could lead to psychological stresses and so it is therefore essential that any future habitat design is very carefully considered with respect to a wide range of criteria and that any proposed design parameters are tested thoroughly in advance and optimised to ensure the well-being of all future inhabitants of Lunar and Martian colonies.

Although current proposals for future Lunar and Martian surface habitats remain at a conceptual stage, it has been possible over many years to study terrestrial analogues within extreme environments to gain an insight into potential future design requirements for extra-terrestrial habitats. Indeed, Moon and Mars analogues on Earth have been constructed for decades and are typically located in extreme locations. They all have rotating crews and attempt as rigorously as possible to simulate aspects of life on other worlds. Well known examples include the Halley VI Research Station in Antarctica, Hydrolab on a marine surface in the Bahamas and the Mars Desert Research Station in Utah, USA. All of these sites have been specifically chosen to support scientific research in an environment of relative similarity to an extra-terrestrial location, whilst at the same time providing opportunities for sample collection, dealing with extremes of temperature and facilitating the detailed study of the location's geographical, geological and geochemical environment and structure. Some have also been selected for their position relative to day lighting patterns [11]. The results of each scientific experiment to date have been carefully recorded and analysis of the data has informed contemporary strategic decision making with regards to the design of future habitats, as well as mission management plans. Simulations are of course a fraction of the cost of sending a crew into orbit and in addition to simulating isolation, they also provide opportunities to study a wide range of procedures with a high degree of safety during emergencies.

In this research project, as far as is possible, the architectural design methodology being proposed has been influenced by a thorough literature review of contemporary terrestrial analogues, analysis of the development of space architecture over the last fifty years and additionally the design principles that guide high quality architectural design on Earth. The architectural principles for designing for extra-terrestrial living proposed have also been influenced by the theoretical environmental and human factors expected to be present off-world. A number of these factors are very challenging to accommodate, but in order to facilitate high levels of habitability and comfort for future crews, an approach to design has to be developed which is holistic but at the same time detailed and technically excellent. Section 2 describes the key architectural design principles for habitability and sets out the main ideologies for designing an architecturally successful environment in space. Section 3 discusses these principles in much greater detail, breaking them down into specific design parameters.

2 Space Habitability Principles

2.1 Space Architecture and Habitability

Today in orbits around Earth, the modular tube-like architectural forms of the ISS and China's Tiangong 1 space station function as off world habitats constructed from components launched individually, in strict sequences and designed to fit within cylindrical rocket launch vehicles. These simple, geometric forms define the architectural language of today's space habitat design and in some sense express a language for space architecture in low Earth orbit (LEO).

Historically, architects have constructed buildings incorporating available local materials and knowledge of construction methods handed down over the generations. For example the Neolithic settlement Skara Brae in Scotland is a simple dry stone structure constructed over 5000 years ago, which blends into the contours of the landscape on Orkney (one of Scotland's northern most islands) and simply utilises the local readily available stone. The explorers and settlers of the New World during the 15th Century also used the resources they found on the new continents they had discovered and applied their previously acquired knowledge and skills as master builders. They did not transport their build-

 DOI: 10.5281/zenodo.202160

ings across the Atlantic Ocean. In the 21st Century the utilisation of available materials on Mars should be no different. Indeed, if we were to launch all the required modules to set up a settlement on Mars from Earth, it would be incredibly costly and inefficient in comparison to using local materials on the surface.

Since the early beginnings of human settlement, innumerable architectural languages and styles have formed unique structures all over the world and their architectural designs have responded to the context of the landscape, the existing architectural typology, the climatic conditions and the use of local materials - in today's metrics the latter activity substantially helps to reduce a building's carbon footprint. Good architecture adopts metrics designed to maximise spatial quality, light, thermal comfort and of course if possible provide aesthetic beauty. These attributes have been well known for centuries and were all summarised by Vitruvius in his book "De architectura" (written in the 1st Century BC) which stated that a structure must exhibit the three qualities of "firmitas, utilitas and venustas" [20]. Put simply, it must be strong, useful and beautiful.

Nowadays, with the development of innovative methods of off-site construction and fabrication, increasing numbers of similar buildings are being replicated across the globe with seemingly little regard to their cultural surroundings and historic context. For example, generic steel-framed structures clad in mass-produced panels can be found in most global cities and towns across the world despite the fact that they lack cultural context and a sense of individuality. In contrast however, there are still multiple examples of architecture exclusive to a specific location and a local material resource, such as the Japanese Shinden-sukuri style characteristic with its historic and cultural influence, the bamboo structures of Indonesia and the earthen structures of Mali and Yemen [19].

Despite the fact that today's space stations are in constant motion and therefore are more likely to be classed as vehicles rather than buildings, these orbiting assemblages are nonetheless still examples of architecture. The current, very topical issue of the possible next step in human exploration of the Solar System would be to initially establish a habitat on the surface of the Moon and Mars, with the intention of continually occupying them, either with a dedicated crew or rotating crews, in a similar manner to the ISS. For these proposals to be successful however, these future settlements must be of a high architectural quality.

A high quality habitat is key to providing a comfortable, efficient and highly flexible and adaptable environment for astronauts. In addition to the engineering design, construction and technical, operational challenges of building settlements on the Moon and Mars, another primary area of concern is the habitat interior. This environment functionally supports human living within the harsh landscapes of the Moon and Mars, but it should also promote a high quality existence for missions which may last for numerous years.

2.2 The Habitable Volume of Spacecraft

With regards to architectural design in space, the most obvious and fundamental factor relates to the specified dimensions and volumes of interior spaces. Habitable Volume (HV) is the free space that one can manoeuvre around within a spacecraft. This excludes any volume occupied by equipment. As a result the total spacecraft volume does not equal the HV (see Figure 1) [22]. Early space missions, since Yuri Gagarin's orbital flight in 1961 in the Vostok spacecraft, were designed to achieve the ultimate goal of putting man in space. The internal environment and human comfort level within Vostok was therefore not a primary design concern, and habitability was not the main priority. The HV fortunately has increased since then as mission duration and crew sizes have increased and comparative measurements are shown in the Table 1 below [13].

Mission	**Habitable Volume (m^3)**
Mercury	1.56
Vostok	1.56
Gemini	1.13
Apollo	1.5
Soyuz	3.3
Skylab	120.3
Space Shuttle	9.25
MIR	50.0
ISS	64.7
Tiangong 1	5.0

Table 1. *Habitable Volume per space habitat*

The earliest missions did not allow much free movement within a spacecraft as the crew were harnessed to their seats for the entire duration of the flight and as can be seen from the table above, habitability for these missions was therefore very low. This parameter has gradually increased over the succeeding decades to the current, more comfortable HV of the ISS. In any future Lunar and Martian habitat, the HV will depend on

DOI: 10.5281/zenodo.202160

a number of factors such as the mission duration, the crew size, the requirement for increased privacy, opportunities to conduct personal hobbies, group activities, increased stowage etc. As a result, it is currently recommended that a HV value of 120 m^3 should be provided per crew member for any future Lunar or Martian mission [22]. Although it is recognised that this HV is a starting point for sizing interior spaces, subsequent design parameters within the HV must be applied to ensure this proposed habitable area is of sufficient size and as high a quality as possible.

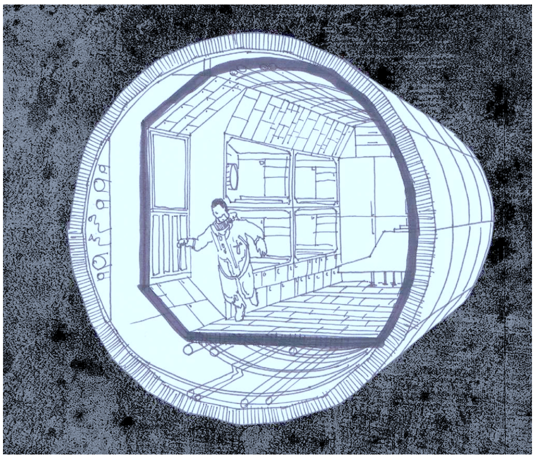

Figure 1. *Highlighted HV and systems volume combined.*

The structural and environmental systems designed within a space habitat are paramount in ensuring human survival. Without engineering excellence space travel would not be possible due to the extreme environments of interplanetary space and the conditions on the surface of other worlds. Proposed extra-terrestrial habitats will therefore require the highest levels of technical ingenuity in order to provide a safe internal environment for crews due to the challenging planetary surface conditions. These testing conditions include high levels of radiation, extreme temperature fluctuations, vacuums, abrasive and adhesive dust, potential meteorite impacts and reduced gravity (see Figure 2). Essentially, without the design of substantial artificial enclosures containing independent atmospheres and environments, life would simply not be possible [25].

The human body and mind is directly affected by its surrounding environment and therefore physical challenges related to anthropometric and biomechanical issues linked to human locomotion and the ergonomics of a space habitat will be major design considerations. For example, the simple action of opening a hatch can be very complex in a space environment; as can manoeuvring between modules. Careful consideration of day to day human activities will therefore be extremely important because the isolation and lack of additional medical care mean that it will be critical to minimise the risk of injury. Therefore the design of every space, workstation etc. will have to be carefully designed and scrutinised.

One of the biggest environmental factors which will affect the human body will be the reduced gravity on the Moon and Mars. This will cause a completely different locomotive (walking or turning around) experience compared to that experienced on Earth. As a result, all details such as furnishings, mechanical devices, supports and restraints will require careful consideration and redesign [4]. Of serious concern is the effect of reduced gravity on muscle and bone mass as well as its effect on other bodily functions such as the digestive system. There could also be detrimental effects on vision and colour perception as well as microscopic changes in the shape of body cells. Whilst architecture cannot directly combat these medical issues and effects, the provision of adequate space to exercise to try to maintain muscle and bone mass is essential, as well as the design of other spaces to perform a variety of other daily tasks. Any proposed HV must therefore be carefully considered at each stage in the design from the overall layout and arrangement of a space through to the arrangement of keypads, buttons and levers [21].

Aside from the physical effects on the human body in a space environment, there are a number of common and more specific psychological and sociological conditions that must be addressed from the outset of the design of a space habitat. Long duration missions will pose greater challenges to astronauts than any mission carried out to date. Long transit times between Earth and Mars, as well as the challenges of living on another world, with reduced gravity for up to three or four years, will be extremely demanding tests of the endurance of the astronauts. Indeed, they will be tested beyond any experience that has ever been encountered by humans to date.

Analysis of the research provided from previous space missions and earth analogues has led to better design solutions which have improved habitability. Although comfort levels are still considered to be low at present with regards to missions over one year in length, this issue is receiving increasing scrutiny in relation to seeking optimum design solutions for a potential permanent habitat on the Moon and Mars.

During the design of a terrestrial building there

 DOI: 10.5281/zenodo.202160

are various design parameters that architects, engineers and designers consider and implement. In the extra-terrestrial design process, environmental factors will have a much greater influence due to the vacuum of space and the thin atmosphere of Mars. In addition, radiation and thermal fluctuations will have significant influence on crew pursuits and will prohibit extra-vehicular activity (EVA) to short periods. The internal design of any habitat will therefore be crucial since astronauts will be confined to interior spaces for the majority of time in any mission and will live in a pressurised environment with a controlled atmosphere, monitored humidity and indoor air quality and regulated temperature and acoustics. Habitats will also need to also provide individual control measures, radiation shielding and sophisticated waste management systems and recycling facilities [3]. A wide range of architectural criteria will therefore have to be applied to the habitat design and these will be studied, adapted and improved over time, in order to achieve the optimum design parameters for high quality and comfortable living environments.

Ultimately a mission's success will depend on the performance of the crew. If any of them become physically or mentally incapable of carrying out their tasks, then the success of the mission will be jeopardised. As well as an individual's comfort and wellbeing the group dynamic will be incredibly important. The crew will have to collectively bond and the architecture should be designed to promote this by providing a relaxing, happy and fulfilling environment which reinforces social positivity amongst all members of the crew. It will be incredibly important to prevent, as far as is reasonably practical, negative interpersonal relations and social conflicts. Undoubtedly, if individuals are housed in a high quality and relaxing environment in which they are content, the mission will be more likely to succeed.

2.3 Psychological Factors

Depending on the particular mission, some astronauts may spend the rest of their careers or even their lives on Mars. These individuals will have particular tastes or styles they consider important and beautiful. Therefore, tailoring the decor, furniture, form and shape of a habitat, which will become their home, will be key to ensure human connections, happiness and a sense of wellbeing. For example, a personal preference of colour could make a difference to an individual's psychological wellbeing and so by implementing the architectural design parameters outlined in the following Section, it

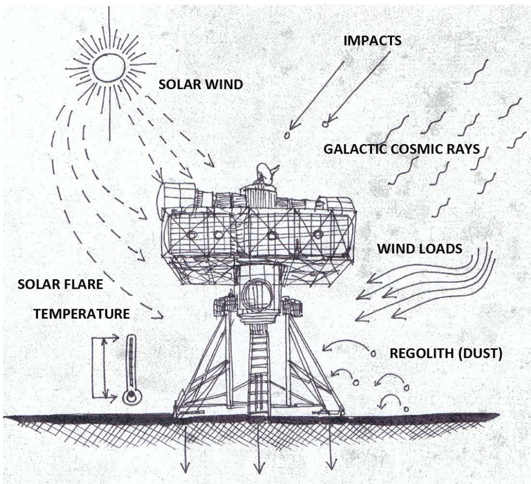

Figure 2. *Environmental threats to a surface habitat.*

will be possible to fine-tune spaces to the requirements and personal taste of individual astronauts thus ensuring comfort and hopefully relaxation and contentment. Individual controls would also be desirable as individuals may prefer to vary daily room temperatures and/or levels of lighting [1].

It is reasonable to assume that a mission to Mars will consist of an international crew. Therefore architectural designs should be flexible to suit a variety of cultural customs, for example, specific religious practices require a space for prayer. Furthermore, to enhance the social cohesion of the crew, the inclusion of specific spaces in accordance with the cultural traditions of individuals and groups should be implemented where possible. As a result, a homogenous, fairly sterile design solution such as the ISS will most probably not be the most suitable design for a permanent surface habitat. Indeed, a combination of cultural elements and varying architectural styles and languages could provide a comforting environment for the entire crew and increase the level of habitability [18].

As has been discussed in this section, architectural quality, comfort and relaxation are all important general architectural principles that will be required of a HV. These broad principles are sub-divided into a number of important architectural design parameters that must be carefully considered. In order to test out the effect and consequences of these design challenges, a basic architectural concept for a Mars habitat has been proposed and developed and is described in the following section.

3 Clarke Base: A Mars Habitat Concept Implementing Architectural Design Parameters

3.1 Overview of the Design

The Mars habitat concept design proposed in this paper, Clarke Base (named after science-fiction author Arthur C. Clarke) takes the form of a three stage construction process as described by Kennedy [15] (See Figure 3). Stage one consists of the delivery of rigid accommodation modules to the planetary surface with a fixed HV. These modules require no further assembly or construction on site and fulfil all requirements for living and working for a short term period of time. Stage two consists of the delivery and deployment of specially engineered inflatable structures. These membranes will require inflation, some frame and support assembly and will facilitate the rapid expansion of an accommodation structure with low volume and a reduced cost from Earth via transit vehicles. Additional radiation protection is required such as a 2-3.0 m layer of loose planetary soil (regolith) piled on top. Finally, stage three will consist of the completion of structures that are manufactured from locally sourced raw materials and constructed in-situ with minimal support from Earth. These structures will require all services and systems to be fully integrated into the fixed and inflatable modules in order to provide flexible habitable spaces.

This prototype Mars community design will therefore encompass a variety of architectural forms utilising structures manufactured on Earth in combination with structures constructed using local materials. It is proposed that these latter structures will employ in-situ resource utilisation (ISRU), which is essentially a construction technique with utilises regolith. In this case the soil is assumed to be the substrate construction material utilised within the structural forms created by large 3D printers. Mars regolith is understood to have similar properties to the aggregate components of high-strength concrete and therefore if printed into a single homogenous structure acting in compression it is hoped that it would have a very good strength credentials [22]. The site selected for Clarke Base, is in the equatorial region of Mars and has been chosen as a suitable location due to the availability of resources, proximity to areas of interest, shelter and available sunlight. From the outset, it is assumed that the habitat systems are technically viable and therefore the following sub-sections describing the design implications of the critical architectural design parameters.

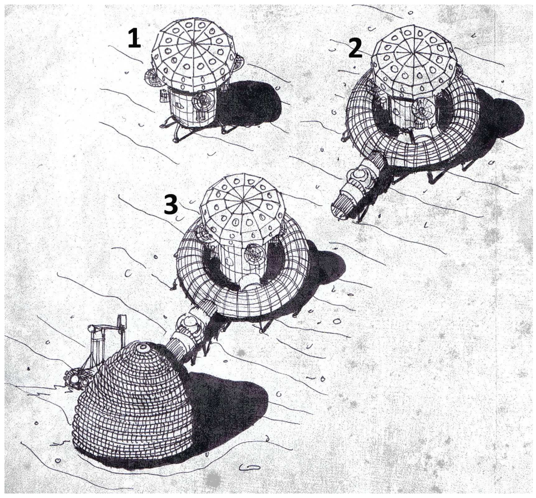

Figure 3. *Three stages illustrated.*

3.2 Arrangement and Layout

From the outset, the accommodation and the layout of technical systems is arranged with regards to an assigned hierarchy of spaces using a system of zoning. This enables the allocation of spaces to be ordered into appropriate arrangements. As with terrestrial architecture, this design strives to demonstrate unity, harmony, contrast, rhythm, balance, order, scale and proportion as well as generate an aesthetically pleasing environment. These design qualities require very different considerations from the functional and purely technical nature of some current space architecture.

All the required facilities within Clarke Base have been categorised into one of the following zones, namely: command and control; engineering; science; medical; transportation and civilian. In addition, the command and control is centrally configured in relation to the other zones to provide quick and easy access to systems from every part of the habitat [2]. Various planning arrangements have been considered in this research study such as a linear, grid and radial. Many of these standard arrangements have been previously tested in a generic form in analogues on Earth and each layout has its own particular advantages and disadvantages (See Figure 4). Some arrangements not regularly seen on Earth are the Contour and Rayed layout but they were proposed to widen the design options and improve the opportunities for quantitative and qualitative com-

 DOI: 10.5281/zenodo.202160

parison. The ISS follows a rigid, linear layout with some nodes and modules forming branches. These orbiting structures however can change with regards to their vertical orientation relative to one another and this makes this arrangement in space a totally different living environment compared to a similar arrangement of modules founded on Earth. When considering linear layouts in a Lunar and Martian context, the presence of gravity would provide a gravitational direction and therefore a uniform vertical alignment throughout the habitat as is experienced on Earth, such as recognisable floors, ceilings and walls.

In order to decide which layouts are the most successful in an extra-terrestrial context, it is important to study the proposed day to day activities of the crew. In long duration missions and permanent structures, there must be provision for adequate space to carry out a variety of activities and this inevitably leads to a high HV. The spaces required range from sleeping quarters and private workstations to kitchen or communal spaces where group activities occur. It is vital to ensure that work, rest and leisure are all conducted in separated spaces to allow for essential privacy and a change in an individual's environment throughout the day. Careful planning of spaces within the zones must also take into account factors such as noise and odour. For example, spaces such as sleeping quarters have not been placed in the vicinity of laboratories [17].

Clarke Base's conceptual layout is shown in Figure 5 and comprises a central rigid module with four surrounding modules. Encircling the central space is an inflatable torus for immediate expansion and this is connected to surrounding rigid modules by elongated inflatable tube-like structures which create additional space. In addition, several inflatable structures branch off these modules allowing for a rapid expansion of the habitat, facilitating the potential development of further nodes and inflatables. The final stage in constructing Clarke Base involves in-situ structures which are constructed once the necessary manufacturing and construction facilities have been established. These in-situ structures are more organic in form and therefore allow additional design freedom for the creation of new Martian architectural typologies, which depart from the industrial and currently monotonous modularity of space architecture. It is proposed here that in-situ structures are arranged in a manner similar to the design of existing villages, towns and communities on Earth. These separate buildings are interconnected through various tunnels and corridors. Each structure will tend to act as a singular dwelling, similar to a house within a village community. This allows a proposed habitat to develop an irregular, pattern which forms unique avenues and crescents; with larger structures forming communal and public spaces.

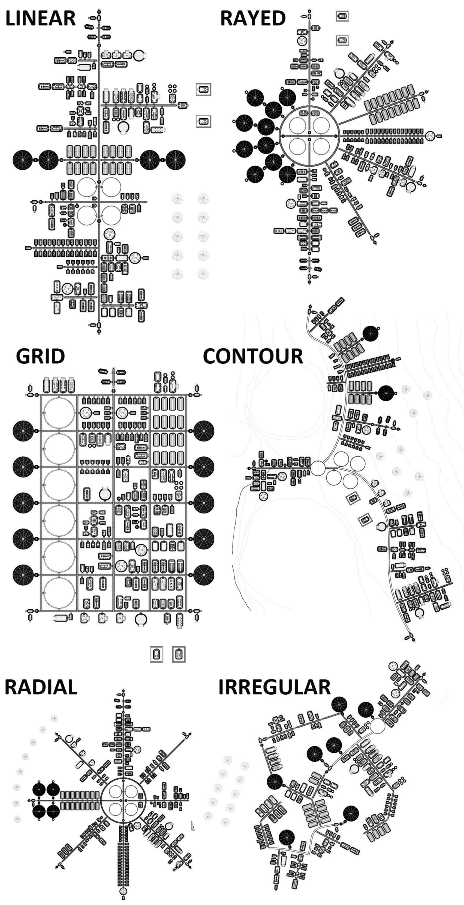

Figure 4. *Examples of proposed modular colony arrangements.*

3.3 Entrances, Thresholds and Circulation

In any building, an important factor is the design and implementation of effective and efficient circulation. This is imperative on space habitats to allow astronauts to ingress, egress and navigate through spaces easily and safely. A circulation network will of course be dependent on the layout of any habitat as a whole, but careful designs should ensure circulation efficiency, comfort and ease. Generally, circulation space is included in the HV of modules, and therefore in this

DOI: 10.5281/zenodo.202160

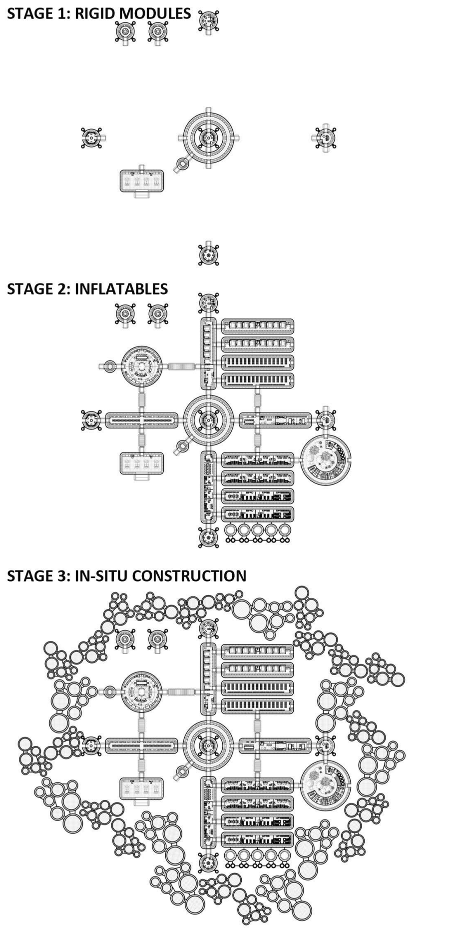

FIGURE 5. *Mars concept design three stage approach.*

radial layout scenario, circulation or access nodes feed the surrounding spaces from a central zone. These surrounding spaces are then connected to each other as the radial pattern suggests, through concentric ringed circulation. Compared to a completely linear arrangement, where access from one end to the other results in the corridors passing through each of the spaces between, radial layouts allow the inhabitants to utilise more direct paths that bypass other spaces. This enables efficient movement and ease of access for maintenance [8]. These considerations are also essential in providing privacy so that crew members bypass sleeping quarters and avoid disturbing their colleagues on different work schedules.

In Clarke Base, circulation is encouraged through connecting nodes and inflatable modules, giving various options to inhabitants to find quick routes through the space station. Entrances from the exterior comprise airlocks and dust-mitigating facilities to avoid internal contamination. Upon future expansion, all private living quarters are relocated to the surrounding stage three structures built from local regolith (see Figure 5), in order to avoid proximity of resting areas to research and experimental facilities, thus avoiding disturbance. With expansion to stage three, it can be seen that the linear arrangement shifts to a more organic form creating unique branches which digress from the main corridor artery. Although this results in a more complex and extended circulation network, the need to exercise, maintain health and avoid monotony are important considerations which benefit from additional translation paths.

3.4 Architectural Form

Space stations have typically consisted of modular cylindrical forms repeated across a linear arrangement [15]. Many future concepts propose similar rigid forms or alternative inflatable structures resembling domes, arches and vaults such as the Mars Homestead project [16]. The form will inevitably be dependent on a number of factors including the volume and internal capacity of the launch vehicle, although it is important to note that inflatable structures and membranes do not have this limitation and can generate various larger forms. The other architectural design proposal considered for Clarke Base includes the use of ISRU, whereby the material for construction is excavated, bound with a binding agent such as metal oxides, assembled and cured into its desired form. Substantial research into this construction option could be the potential solution to providing an efficient, relatively low-cost design that allows greater freedom of expression. This form of construction would most probably rely on some form of robotic machinery and it is conceivable that any form could be created by means of specially designed 3D printers or similar technologies. These could potentially manufacture complex geometrical forms including, domes, vaults and arches. These structural systems would then have the opportunity to include multiple levels, ramps, staircases, and natural, organic-shaped layouts. In addition, building elements such as bricks, columns and beams could be constructed and then erected on site by machinery or astronauts giving rise to multiple variations in architectural form and aesthetics [23].

 DOI: 10.5281/zenodo.202160

3.5 Ergonomic Design

In addition to the overall architectural planning and organisation, space habitats must consider detailed human dimensional design and ergonomic requirements. Investigation and development in these specialist fields has informed the minimum requirements for the dimensions of habitats in reduced gravity and their furnishings and common examples include dimensional specifications for workstations and dining tables. For example, an astronaut seated at a workstation in reduced gravity has a specific range that his/her hands can reach and interact with a control panel. This range will be different compared to their equivalent measurement on Earth. It is therefore important that in extra-terrestrial environments, detailed consideration is given to every detail to ensure that essential movements and interactions with controls are designed to be at comfortable positions. This will facilitate a comfortable and productive working environment [7]. As the arm range or reach vary depending on an astronaut's body dimensions, it is important to set up guidelines which define dimensions which are valid for the vast majority of astronauts, in the same way as guidelines on Earth for components such as handrails, stairs, ceilings and doors have specified minimum and sometimes maximum heights. For any future mission to the Moon or Mars, each individual piece of furniture or architectural element such as a staircase, bench etc., would have to be carefully considered and designed appropriately for the particular level of gravity as reduced gravity affects the locomotion of human limbs. These standard elements will therefore require further investigation and redesigning due to reduced gravity and this can be carried out by utilising anthropometric and ergonomic experiments. In summary, the dimensions of day to day interior furnishings which we use without thinking and are considered appropriate for Earth architecture will no longer be entirely relevant. They will instead act as a foundation for future research. Whilst the astronauts will eventually adapt to the level of gravity on their host planet, their maintenance of fitness levels will likely affect their locomotion. This may mean that in long term missions some architectural elements may require further redesign to accommodate changes in human physical capabilities.

In Clarke Base, illustrated previously, Martian gravity of 0.376 g has been taken into account for the design of all spaces within the modules and the ISRU structures. Ceiling heights have been set at a minimum level of 3.0 m and all reach envelopes and translation paths have been carefully analysed in order to provide enough space for inhabitants to navigate and work within the habitat with ease and an assurance of safety. Stairs for instance have been avoided where there are multiple levels and replaced instead with ladders in order to avoid an accident due to a change in human locomotion in reduced gravity.

3.6 Adaptability and Flexibility

For long duration missions it is important to avoid monotony in order to look after the psychological wellbeing of the crew. As on Earth, individuals will probably wish to change their interior decor or rearrange furniture as they would do in their homes. Whilst the main habitat structure shape will remain constant, the internal layout and the opportunity to add extensions is an important consideration to help facilitate flexible and adaptable design. Astronauts living on the Moon and Mars may desire change periodically. It is therefore essential that interiors can be altered to a certain degree to thereby increase the feeling of homeliness. This could mean the inclusion of sliding, rotating or collapsible walls to alter the internal layout of spaces, as well as the means to rearrange furniture, system racks and equipment [7].

The Clarke Base modules illustrated below have therefore been designed with folding and sliding components to allow a change of spacing and zoning as per the astronaut's desire. A simple grid system with a click-in mechanism also permits walls and furniture to be rearranged in various layouts. This would work in a similar manner to the rack system on the ISS, which provides adequate storage space and facilitates workstations etc [17]. The initial layout is of course optimised for space utilisation, however astronauts may desire change over time with respect to their requirement for a larger space or their need for additional privacy. The capacity to allow multiple arrangements for interiors has been considered from the outset to ensure that furniture, walls and other components can be rearranged with ease and assurance (see Figure 6).

3.7 Light

Natural light is the most desirable form of light on Earth to illuminate a space. It provides natural endorphins which lift the human spirit and is a natural source of Vitamin D. It also produces no sound unlike the noise intrusion sometimes caused by artificial

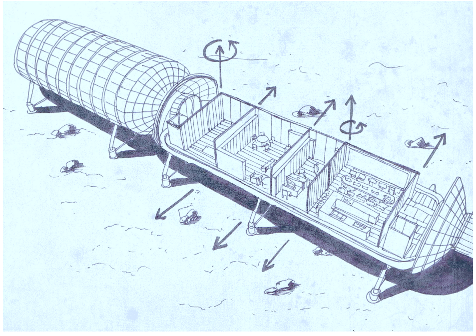

Figure 6. *Flexibility of internal wall configurations.*

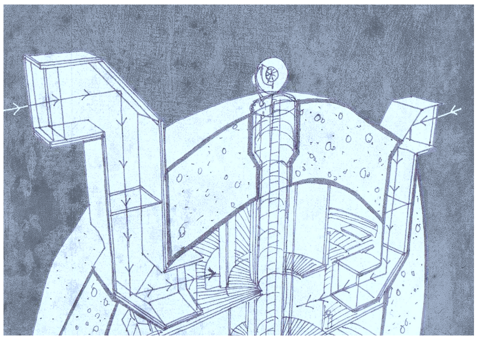

Figure 7. *Periscope with filters for natural light and views.*

lighting. Architects and designers strive to design buildings on Earth to maximise natural light. They employ mechanisms and techniques to flood interiors with light due to its well-known positive effects both physically and mentally. Indeed, entire architectural schemes have been built around the requirement to harness natural light and these have created distinctive and aesthetically pleasing forms. Whilst the intensity of sunlight experienced on Mars will be lower than on Earth, it is still advised that light be captured wherever possible to illuminate spaces naturally [24].

Unfortunately windows are considered to be a structural weakness in pressure vessels and are hazardous with regards to radiation exposure. They also pose an additional hazard as they would require EVAs to repair, clean and maintain them externally. For these reasons, it appears sensible to minimise the amount of windows in a space habitat in order to minimise risks. Unfortunately this reduces the level of habitability and therefore a compromise must be found which keeps the crew safe whilst allowing them to live in as exciting and stimulating an environment as possible.

Clarke Base incorporates natural light into the habitat through a system of angled mirrors, assembled within a structural framework similar to large periscopes (see Figure 7). In addition, special filters have been fitted to prevent radiation entering the space. Light is therefore gathered and channelled into multiple rooms through technologies designed to rotate and follow the sun's path. Additionally, to maximise light penetrations as much as possible, certain internal surfaces are coated in reflective materials to help distribute the light more effectively [6].

3.8 External Views

A connection to the outside world is vital, especially in a remote and distant region on the Martian surface, which will be new and exciting. There is a practical necessity for external vistas to facilitate docking procedures and provide direct views of external activities as well as possibly provide opportunities for space photography. Observing Earth from the ISS is a favourite pastime of many astronauts. This prompted the installation of the cupola window in 2010. Views towards the Earth, Moon and galaxy are a source of visual stimulation and a chance to escape the confinement of any space accommodation. These openings and vistas effectively expand the perception of the internal zone and psychologically provide a closer link to the exterior landscape [24].

On Earth we are surrounded by gardens, seasonal colours and changes, sunsets, wind, vegetation, buildings and art. On Mars these stimulants will not be present to the same degree. Whilst the Martian landscape appears interesting and captivating from afar, it does not contain life or the multitude of distractions that the Earth offers. Simulated windows and artificial or synthetic views can offer both visual stimulation and ensure maximum structural integrity of the module. These high resolution screens can cover large areas within the interior - larger than a window - and could display a sky, ocean, forest or mountain: instantly transforming the enclosed interior vessel to one with a view of nature and a connection with home.

Clarke Base contains large viewing areas with additional radiation filters and it is proposed that time limits would be included to reduce exposure to radiation [6]. Modules where astronauts will sleep for several hours, potentially absorbing radiation, have no natural lighting or views, again to minimise the exposure. Instead,

 DOI: 10.5281/zenodo.202160

sleeping quarters have been designed with large screens to simulate views of either the exterior or an environment on Earth as the crewmember desires.

3.9 Space Design and Perception

The perceived dimensions of a space can be altered without changing the volume. This can be achieved by the implementation of curved elements instead of angular ones with defined edges. In spaces of identical volumes, rooms with curved walls and surfaces appear larger than those with angled corners. Within the ISS the cylindrical form contains a cuboid volume internally, due to the position of workstations and storage racks. Despite being cylindrical in form, the internal space has defined edges and lines that connect to one another [12]. Replacing this with curved lines with no ends creates the illusion of a larger volume, as the perceived dimensions appear continuous or infinite within the space. These techniques could be used to make spaces within the habitat appear larger without increasing HV (see Figure 8). This may be beneficial when some zones are required to be a certain size due to constraints on materials or available space for construction. It is also beneficial to design spaces with irregularly shaped floor plans, such as an 'L' or 'S' shape so that an entire space cannot be observed as a whole from a certain vantage point. This is also true for any spaces with multiple levels or variations in ceiling heights [9].

Clarke Base's curved forms and floorplans, particularly in the stage three ISRU structures, give the spatial perception of larger spaces internally, which are further broken up by panel walls, dividers and specific curved furniture elements to create spaces within spaces. Due to the design freedom of 3D printing and microwave sintering, stage three spaces are designed as a variety of curved walls and ceilings, spaces which extend around corners using various dimensions in order to give the appearance of grander spaces (See Figure 8).

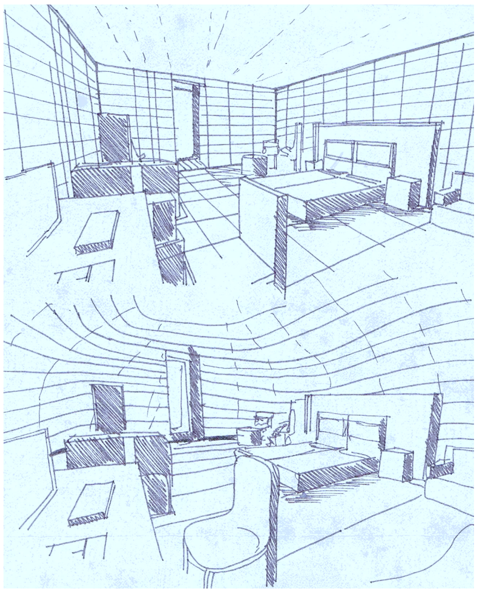

Figure 8. *Spatial perception: edges vs. curves.*

3.10 Decor

Simple factors such as the colour of the interior walls, floors and ceiling are important for psychological well-being as is the identification of colours in specific spaces for aiding the crew's perception of orientation in microgravity. A multi-sensory environment can affect the mood of the inhabitant, promote tranquillity, increase performance and boost morale [10]. Overall, colour and texture amongst other decor elements, can be incorporated in relation to living in space and it is hoped that this can have a profound impact to various degrees in reduced gravity scenarios. The saturation, hue, contrast, brightness, tone and distribution of the colours used are also important factors for the habitat's interior. The intensity and quantity in terms of the number of different colours used within one space is also an important factor, as too many variations of colours can be too intense, distracting and overstimulating, whilst more subtle changes are perceived to be more desirable. However some of these decisions again come down to individual preferences and it would be important to allow freedom of colour choice within individual, personalised areas of the habitat. As with the perceived dimensions of a space, the colour of the interior can also create the illusion of a smaller or larger space as well as create a distinct atmosphere. These techniques can be used in order to make a space seem much larger than it truly is [5].

The Russians, through Salyut and MIR, experimented with the use of colour to help give an orientation to their space stations, giving the ceiling a lighter colour than the floor [17]. On the Moon and Mars this will not be an issue, but it is still worth considering colour in setting the tone or mood of an environment and avoiding sterile white spaces. A variation of textures is also an important consideration to avoid monotony and stimulate the senses relating to touch. Subtle differences can indicate different zones and provide connotations of comfort in areas set aside for resting for example. [17].

In Clarke Base, the internal colours vary throughout the habitat depending on the zones. Warm tones of red and orange are used in rest areas; colder tones of blue and green in areas of work, and clinical whites in spaces that require high degrees of hygiene. Individual or group spaces are decorated according to personal preferences with no limitations, therefore these areas would require consultation with the crew. The spaces are, as far as possible, designed like any interior home or work space, employing patterns and designs as well as solid colours. A variety of colour palettes and textures are used either by way of the materials chosen or through artificial displays. These allow any desired image to be projected onto the walls, ceilings and floors, creating a dynamic multi-sensory environment. Coloured lighting is also incorporated to enhance the quality of a space as well as replicating natural colours – for instance that of a sunrise.

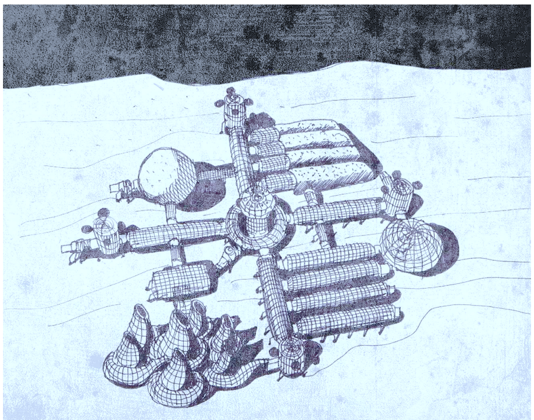

Figure 9. *Mars concept design with all three stages.*

4 Concluding Remarks

This paper has highlighted the key architectural design parameters essential to ensure the functional success of a space habitat and has also explored the less easily defined criteria which relate to psychological, physiological, cultural and emotional human characteristics. Generating holistic proposals which encompass all of these widely varying criteria is complex and challenging, but an essential part of space exploration planning. Specific civil engineering technologies such as ISRU constructed potentially using 3D printing, will allow the freedom to design structures of numerous architectural forms (see Figure 9) and permit future space architects to generate a novel and unique style based on the Martian or Lunar location and landscape. Indeed, in a sense, the architecture of a specific region on say Mars could become distinguishable and unique from another Martian region, just as Architecture is currently differentiated between different climatic zones, regions and cultures on Earth.

Aside from the generation of new architecture, the design parameters discussed in Section 3, which include ergonomic design challenges in response to lower gravity, could form part of a new extra-terrestrial architectural handbook. This document would require architects to design structures in accordance with extra-terrestrial planning and design data in a similar manner to the guidelines followed by Architects that are described within the UK Metric Handbook on Earth. This document describes architectural spatial planning rules based on ergonomics, good practice, construction techniques, health and safety and cultural norms and is fully integrated into the UK's building regulations and associated legislation [26]. Whilst a current guide exists for the interior design of habitats in orbit (NASA-STD-3001 and associated texts) [4], it is proposed by the authors that the above architectural manual or handbook is required for the design of structures on the Moon and Mars.

The literature review of previous spacecraft, space stations, terrestrial architecture and analogues, suggests that this holistic technical manual should contain minimum dimensions and ergonomic parameters developed to cover a variety of architectural design considerations. It must also contain important architectural parameters that generate designs, which can be implemented, tested and improved continually through experimentation and research. Throughout the lifespan of any structure on another celestial body, it is important to provide guidelines for delivering minimum requirements for achieving comfortable, stimulating and relaxing environments for future colonists. These "architectural instructions" would encompass aesthetic and spatial architectural design as well as HV and psychological factors. In particular the key design parameters of form, space, order, arrangement, layout, ergonomics, adaptability, natural lighting, views and interior decor.

To ensure these design parameters are optimised before surface habitation is implemented in reality, it is recommended that more analogue experiments are carried out within terrestrial analogues on Earth, such as a live build of Clarke Base or other concept designs.

 DOI: 10.5281/zenodo.202160

These experiments, which should utilise ISRU and be conducted in isolation, could carry out detailed social research into the way that large groups cope with isolated construction projects and prolonged periods of time in extreme climatic environments. It is hoped that through rigorous research and a detailed understanding of how highly trained individuals work and live together in artificial environments, this will allow scientists to carefully prepare potential future Martian pioneers for the journey and life ahead of them. It should also ensure that astronauts are psychologically and physically prepared to meet the challenges that they will encounter thereby ensuring the maximum possible opportunity for colonisation success.

References

[1] C. Allen, R. Burnett, J. Charles, et al. Guidelines and capabilities for designing human missions.

[2] H. Benaroya. *Turning Dust to Gold: Building a Future on the Moon and Mars.* Praxis Publishing.

[3] H. Benaroya, L. Bernold., and K. Chua. Engineering, design and construction of lunar bases. 15(2):33–45.

[4] J. S. Centre. *NASA-STD-3000 Man-System Integration Standards.*

[5] Y. Clearwater. Space station habitability research. (17):217–222.

[6] B. Cooper, D. Schrunk, and B. Sharpe. *The Moon: Resources, Future Development and Settlement.* Praxis Publishing Ltd, second edition.

[7] W. Dempster. *The Anthropometry of Body Action.* Number 63 in Annals of the New York Academy of Sciences.

[8] O. Doule, V. Šálený, B. Hérin, et al. Omicron space habitat - research stage ii. (70):139–158.

[9] T. Dubbink. Designing for har decher: Ideas for martian habitats in the 20th century. https://goo.gl/ZUavSQ.

[10] A. Harrison. *Spacefaring: The Human Dimension.* University of California Press.

[11] A. Harrison. Humanizing outer space: architecture, habitability, and behavioral health. *Acta Astronautica*, (66):890–896, 2010.

[12] B. Imhof. Configuration options, habitability and architectural aspects of the transfer habitat module (thm) and the surface habitat on mars (shm)/esa's aurora human mission to mars (hmm) study. (60):571–587.

[13] R. Johnson and J. Stepanek. *Fundamentals of Aerospace Medicine.*

[14] A. Kalery, I. Sorokin, and M. Tyurin. Human space exploration beyond the international space station: Role of relations of human, machine and the "earth". (67):925–933.

[15] K. Kennedy. The vernacular of space architecture. https://goo.gl/93kkDt.

[16] B. Mackenzie, B. Leahy, G. Petrov, et al. The mars homestead: a mars base constructed from local materials. (7472):1–17.

[17] V. Martinez. Architectural design for space tourism. (64):382–390.

[18] V. Martinez. Architecture for space habitats. role of architectural design in planning artificial environment for long time manned space missions. (60):588–593.

[19] M. Moffet, M. W. F., and L. Wodehouse. *A World History of Architecture.* Laurence King Publishing.

[20] V. Pollio and M. Morgan. *Ten Books on Architecture.* Dover Publications.

[21] C. Rando, S. Baggerman, and L. Duvall. Habitability in space. In editor, editor, *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting*, number 49, pages 5–9.

[22] J. Ruess, F. Schaenzlin. Structural design of a lunar habitat. (19).

[23] G. Sanders and W. Larson. Progress made in lunar in situ resource utilization under nasa's exploration technology and development program. (26):5–17.

[24] M. Seguin. Engaging space: Extraterrestrial architecture and the human psyche. (63):980–995.

[25] E. Steinberg and W. Bulleit. Considerations for design criteria for lunar structures. (7):188–198.

[26] R. Surveyors. Metric handbook. https://goo.gl/JkcTLV.